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QUALITY FEATURES OF SPACECRAFT BALL BEARING SYSTEMS

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INTRODUCTION

Ball bearings are used on virtually every spacecraft launched by GSFC. The bearings represent a variety of sizes and are procured from a variety of bearing manufacturers. In almost all cases, the sizes, materials, and sources of the bearings are determined by the contractor's or component manufacturer's designer, based upon hardware configuration, cost, and availability.

Also, in almost all cases, the procurement specifications for the bearings spell out requirements that are not important to the quality of the bearings, while concomitantly ignoring details which are important. Because the volume of spacecraft bearings that are purchased represent only a small portion of the output of most manufacturers, some specification requirements at times are not followed if they would impact the normal production operations. Conversely, normal production procedures that are deemed undesirable by NASA, such as ultrasonic cleaning, may be imposed upon the bearings by the manufacturer.

It has been the practice, in most instances, for the contractor or component vendor to procure and install the bearings into the motor or device without benefit of any significant inspection. Subsequent failures of the bearings during testing in many cases revealed defects of various sorts, such as reversely-installed shields and non-final-finished ball grove surfaces, contaminated lubricant, and non-specified ball cage material. The fact that such defects and discrepancies were found on failed bearings in test implies that they may have existed in bearings that were launched on flight hardware and subsequently failed in orbit. It is apparent that proper specification and adequate inspection would have found at least some of the defective bearings.

This report is written to call to the attention of all persons using and purchasing ball bearings, those aspects of bearing quality which are often overlooked. It is hoped that knowledge of the contents of this report, by those concerned, will help to avoid premature failures of bearings on future spacecraft.

UNDESIRABLE TREATMENTS

Ultrasonic Cleaning. One of the standard processing operations that are conducted by most bearing manufacturers is that of ultrasonic cleaning of assembled bearings. A study conducted at GSFC (Ref. 1) disclosed that such a treatment can result in sufficient fretting between the balls and races as to cause gross scratching that degrades a fine surface finish, as shown in Fig. 1.

Ultrasonic cleaning is a recommended procedure to clean porous materials, such as phenolic laminate ball cages and nylasint reservoirs, because the vibrational energy assists in the removal of contaminants from the pores. However, this treatment should be performed on the porous piece parts alone and not after they have been installed into the bearings. The bearing races and balls should be subjected to various solvent exposures before they are assembled as a bearing and, therefore, ultrasonic agitation should not be necessary after assembly.

Passivation. Some bearing manufacturers routinely subject bearing parts made of 440 C steel to a chemical passivation treatment according to Fed. Spec. QQ-P-35 (Ref. 2), which calls for a hot nitric acid exposure. This specification was written to remove tramp metal particles from austenitic stainless steel fasteners to prevent the formation of ugly rust and corrosion spots; it was not written for ball bearings.

Ball bearings, especially those for spacecraft applications, should be solvent cleaned enough times during manufacture and storage and handled carefully so that they should be free of any minute tramp elements on the surface. However, even if there were such tramp element particles on the bearing metal surfaces, they should pose no problem because of the relatively benign corrosion environments to which the bearings are exposed and because of the protective film of oil on them, when lubricated with oil or grease. Any such corrosion danger problem on 440 C steel bearings should be significantly less than the corrosion danger on bearings made of 52100 steel, which is a common spacecraft bearing alloy.

The objection to the passivation treatment is that it does chemically attack the steel and creates a micropitted surface, as pictured in Fig. 2. There is a good possibility that, during the passivation treatment, bearings may be left forgotten within the passivation bath for an unnecessarily long time and, thereby, result in an exaggerated pitted condition, as indicated in Fig. 3. The pitting alters the surface smoothness and, thereby, affects the thickness of oil required to develop hydrodynamic or elasto-hydrodynamic lubrication. Needless to say, HD or EHD lubrication are the desired conditions for long life. If the bearings are to be lubricated with a solid film, such micropitting may not be serious.

Abrasive Tumbling. At least one bearing manufacturer routinely tumbles assembled bearings of a certain ball size and smaller, as a batch operation in a ball mill setup with an abrasive slurry. The time of tumbling is many hours and, as the ultrasonic cleaning, it promotes microabrasion scratching and pitting. In fact, the reason why the bearing manufacturer employs this procedure, reportedly, is to improve the surface finish by wearing away the high spots. Fig. 4 illustrates the ball groove surface before and after such an exposure; the photos suggest that the surface finish is degraded, rather than improved.

By logical reasoning, one can ask why the bearings with larger size balls are not tumbled, also, if the procedure improves the surface finish, as stated. Perhaps the bearing manufacturer falsely believes that a finer surface finish is not necessary for larger bearings, or it finds that the larger and heavier bearings are not amenable to the proprietary process. And, because the process is proprietary, this is just another reason for avoiding it.

Hot TCP Coating. Tricresylphosphate (TCP) (Ref. 3) is added to oils to serve as an extreme-pressure lubricant by coating the metal surfaces with a phosphate film.

Reference 4 lists some test results to show how the TCP, incorporated into the oil, improves the wear resistance. Some years ago, M.I.T. performed some studies (Ref. 5) which led to their development of a hot TCP coating procedure. This procedure subjects assembled bearings to five separate ultrasonic cleaning exposures, each of five minutes duration. The dangers of ultrasonic agitation of assembled bearings have been described earlier in this report.

The contention being made here is that, if TCP is to be employed to provide improved wear resistance, it is more advisable to add it to the oil rather than to subject the bearings to the possible damage of the M.I.T. process. Indeed, even M.I.T. adds the TCP to the oil, even though they may have employed their hot coating process. Visual examination at GSFC of TCP-coated bearings at various magnifications did not reveal any phosphate film; so, the effectiveness of the coating process in applying a lubricative phosphate film is suspect.

Grease Plating. One practice employed by some vendors is that of lubricating the bearings by means of a grease plating process. In this process, the grease is thinned to some desired fluid consistency with a suitable solvent, and the cleaned and assembled bearing is dipped one or more times in the liquified grease, thereby coating all surfaces with a thin layer after the solvent has evaporated. This practice has a number of disadvantages:

1. All surfaces are coated, inside and outside, which requires some cleaning of the exterior to remove excess grease if meaningful weight measurements are desired.
2. The amount of grease added is usually very little, and its effectiveness thereby is questioned.
3. There is the danger that the solvent may not evaporate easily and may slowly exude to cause chemical reactions or other problems after installation of the bearings into the device.
4. There is a danger that the solvent may have affected the properties of the grease to degrade its performance. Friction and wear tests have shown this to be true of Andok C and toluene.

If grease plating is resorted to, the liquifying agent should be the base oil from which the grease is formulated. However, it is considered more desirable to inject the required amount of grease directly into the ball groove by means of a hyposyringe.

Burnished-on Solid Films. Some solid-lubricated bearing procurements call for a solid-film of MoS_2, or other lamellar solid, to be rubbed on to the balls and races. Sometimes this burnished-on film is in conjunction with a soft plastic ball cage made predominantly of teflon or polyimide for additional lubrication of the transfer-type. The application of such sparse and poorly adherent films add to the cost of the bearing without adding much, if anything, to its performance.

The application of MoS_2 (or other lamellar solid) to a bearing should result in a well-adhered, continuous, and thin film. Some so-called burnished films are applied by the manual rubbing with an MoS_2-coated cotton swab, with the result that little is applied. Another such process inpinges an MoS_2-coated medium against the bearing surfaces under air pressure with the result of some microscopic dimpling of the surface occurs that roughens the surface but adds very little of a poorly-adherent coating.

There are very few good burnished-on MoS_2 film processes. Even the process developed by NASA-Lewis, which involves an argon atmosphere and a high-speed rotating stainless steel brush to apply the MoS_2, does not result in a well-adherent, continuous film. The best films are obtained primarily by rf or dc sputtering or by high-temperature-cured sprayed-on processes (Refs. 6 and 7).

UNDESIRABLE CONDITIONS

Soft Metal Cages. One of the ball cage types that are available for ball bearings are called crimped-ribbon type because they are made of two stamped circular metal ribbons of stainless steel that are crimped together by tabs on one ribbon circle. Figure 5 illustrates this type. Because the tabs must be soft and ductile enough to permit the crimping, the ribbons are made of soft austenitic stainless steel. Additionally, the ball pockets, which are formed in the stamping operation, encircle the balls and, therefore, overlap the ball groove into the race land area. If the cages are made to be guided on either the inner race land or the outer race land, then the rubbing contact they make with these generally-rough surfaces can result in the generation of significant wear debris, as well as in lubricant degradation. Figure 6 pictures the wear developed by such a ball cage.

Coarse Surface Finishes. In oil- or grease-lubricated bearings, the aim for long life is the establishment of a hydrodynamic or elastohydrodynamic oil film between the balls and the races. The thickness of oil film required to achieve this condition is partly dependent upon the surface roughnesses of the balls and ball grooves. Figure 7 pictures the types of surface finishes that have been noted on the balls and ball grooves of various bearings; the range represented is significant and cannot be adequately revealed by conventional surface profilometer measurements that give RMS, AA, or CLA values.

Ball bearing manufacturers employ a variety of surface polishing procedures and can consistently produce ball groove finishes of less than two microinches RMS, if requested. Such a finish should result in a peak-to-peak surface roughness of less than five microinches. Balls normally have much better surface finishes than the ball grooves. Inasmuch as most bearing manufacturers procure their balls from other vendors, there is little they can do to improve the finish, but there is much they can do to degrade the ball finish.

A good way to specify surface finishes of balls and ball grooves is to require the bearing manufacturer to produce the best that he can, and to provide 200x photos of ball and inner-race groove surfaces to verify that the finishes are acceptable. If bearings are equipped with ball cages that are guided on the lands of either of the races, then the land finishes should be reasonably smooth, but not necessarily as smooth as the ball grooves because of the light loads and intermittent contact between the cage and the lands.

Corrodible Steel. In spacecraft bearing applications, the two most common steel alloys used for the balls and races are Type 440 C stainless steel and AISI 52100 steel. Both alloys can be heat treated to a high hardness (approx. 60-65 Rockwell C max.), which is recommended for low wear; however, the 52100 is much more corrodible than the 440 C because of its lower chromium content.

The higher susceptibility of the 52100 steel to atmospheric corrosion is a disadvantage to its use in spacecraft applications because there is usually a minimal amount of liquid lubrication present which could serve to coat the entire surface and protect against corrosion, as well as provide the lubrication. Therefore, wherever possible the 440 C steel should be selected over the 52100.

Admittedly, some bearing sizes might not be available in the 440 C steel and, therefore, must be procured in the 52100 grade. In such cases, once the bearings are received from the manufacturer, they must be more rigorously protected against staining and corrosion from handling and from the environment.

Impure Cages and Reservoirs. In general, bearings that are to be lubricated with oils or greases should be equipped with porous, non-metallic ball cages that are vacuum impregnated with the oil being used. The most commonly used of such cage materials are cloth-laminated phenolic, sintered nylon, and sintered polyimide. Each of these are subjected to moisture and machining coolants and other possible contaminants, which should be removed prior to the vacuum impregnation. In addition, some of the cotton-cloth phenolic laminates employ unbleached cotton which contains cottonseed and weaving oils and sizing starches.

The phenolic laminate that is recommended for ball cages should be made of bleached cotton (Synthane LB or LBB grade, or equivalent) and should be required to be porous enough to absorb oil as a minimum of two percent of its weight in the impregnation, with the excess surface oil removed. The porous nylon and polyimides normally absorb more than twenty percent of their weight of oil.

The removal of contaminants from the pores of these cage materials is critical. One proven thorough method to accomplish this cleaning is that of soxhlet extraction for 24 hours in a reasonably strong solvent, such as ethyl alcohol-chloroform, hexane, or xylene. Another method would involve a number of 15 minute ultrasonic exposures in hot baths of one or more of the mentioned solvents, but not while in assembled bearings. Other similar methods may be used. However, before the impregnation, the cleaned porous cages should be thoroughly vacuum dried at elevated temperature for several hours in order to remove the solvents. Recommended conditions are a pressure of less than 1000 microns, a temperature of about 60° C or more, and a period of 4 hours or longer.

The above statements apply as well to oil reservoirs that are normally fabricated from sintered nylon.

Broad Preload Range. Bearings which are to be subjected to an axial preload should be dimensioned accurately to provide a known and narrow preload range. If HD or EHD lubrication is not achieved in an oil- or grease-lubricated bearing, and in a solid-film-lubricated bearing, the life of the lubricant and of the bearing is directly related to the load between the balls and the races. The preload determines the ball load in a zero gravity field and, therefore, it should be as low as is necessary.

Axial preloads can be applied to bearings in many ways: by coil springs, flex diaphragms, wavy washers, belleville springs, and nuts, to name several. The spring-type load appliers can be calibrated so that the preload can be accurately known. Nut-type load appliers require the bearings or spacers to be ground a precise amount to correspond to a precise axial preload when the bearings are assembled against hard stops and spacers.

It is conceivable that wear and vibration can cause a change in the preload of hard-mounted bearings; whereas, spring-loaded bearings maintain a relatively constant preload. Therefore, spring loading is the better method.

DESIRABLE TREATMENTS

Adequate Inspection and Lubrication. The processing of ball bearings for spacecraft applications is too important to leave to chance and to blind faith in the bearing manufacturer without adequate inspection. There have been too many instances of faulty conditions or improper lubrication in bearings, as received from the manufacturer. The number of such instances undoubtedly would have been greater had there been more after-receipt inspection.

Bearing manufacturers are not geared to process spacecraft bearings in the careful manner in which they should be processed. Their production procedures do not easily accommodate changes that are deemed desirable for the small number of spacecraft bearings. For example, if a strong solvent, such as chloroform, for cleaning bearings is requested, they may refuse because it complicates their procedure from the personnel hazard standpoint. If vacuum impregnation of bearings with a heavy oil at low pressure is desired for a period of a day or two to ensure complete exhaustion of air from the porous cages, again, refusal may be met because of inadequate vacuum equipment or because the equipment cannot be reserved that long.

Accordingly, NASA contractors often accept what they can get from the bearing manufacturer, being satisfied that the components are of good quality without further inspection or verification. However, such simple inspection steps as checking the composition of the lubricant, on occasion, has revealed that it was not as specified. Such past experience has made it desirable to seek other facilities for the final inspection and lubrication steps. In lieu of outside assistance in the lubrication, the least that should be contemplated to check the quality of the bearings is a complete inspection of a random sample of the bearing lot, down to the point of disassembly and microscopic examination of surface finishes.

Deburred Ball Cages. Ball cages are made of a variety of materials, although the hard metals or oil impregnated plastics are preferred. Because of size, perhaps only stamped-out and welded or brazed bronze cages are available. Such stamped-out cages have sheared edges that may contain metal burrs that can serve as debris in the bearing. In like manner, machined phenolic or sintered nylon or polyimide, or teflon-base cages, are sometimes produced with sharp edges that are easily damaged and are a source of particulate debris. However, these same cages are provided by other vendors (or even the same vendor at other times) with nicely-rounded and deburred edges that are not sources of debris.

This variability in the quality of the ball cages is due to the fact that little attention is given to them by the purchaser and, consequently, by the vendor. Figure 8 shows two teflon-base cages from the same vendor with significantly different finishes. This same variability has been seen in laminated phenolic cages.

Polished Race Lands. In most instrument bearing sizes, the ball cage is made to be guided on the lands of either the inner or the outer race. This means that there are many cases of rubbing contact between the cage and the land. Although the forces at such contacts may be low, wear can occur if an inadequate lubricant exists. As stated previously, the smoother such contacting surfaces are, the thinner need the oil film be to keep the surfaces separated, and the less the friction and wear will be. Therefore, the lands that will be in rubbing contact with the ball cage should also be processed to a reasonably fine finish, although not necessarily as fine as the ball groove.

Anti-Creep Barrier Film. One of the concerns with oil lubricated bearings is that of the possible creep of the oil from within the bearing to surfaces outside of it, with a consequent reduction in lubricating effectiveness and bearing life. The creep of the oil is dependent upon several factors, including the surface energy of the oil and that of the bearing surfaces. Some oils, such as the silicones and the perfluoropolyalkylethers, have the lowest surface energies and creep the most.

In order to minimize the creep, the bearing faces and the contiguous areas outside of it can be coated with a fluorinated methyl methacrylate developed by the Naval Research Laboratory, called an anti-creep barrier film. The film and its usage are described in detail in Refs. 8 and 9. The latest developed barrier film contains a fluorescent agent which permits examination after application by UV light. Needless to say, caution must be exercised to prevent incorporation of the barrier film within the bearing itself.

DESIRABLE CONDITIONS

Bearing Shields. One simple technique that can be used to inhibit the loss of oil from bearings and to help prevent the ingress of particulate and other contamination is that of the use of shields on them. Double shields, i.e., one on each side of the bearing, are more protective than a single one.

The use of shields on the bearings have a few disadvantages that require some precautions. First, the shields make visual inspection of the bearing interior almost impossible. Therefore, the spring clips that retain the shields should have angled ends to permit easy removal. Second, there should be some clearance between the inside surface of the shield and the ball cage to prevent rubbing contact between them. Third, if only a single shield is used on a bearing with a crown-type ball cage, the shield should be on the open side of the crown. Fourth, if a single shield is used on each bearing in a pair, the shield should be installed on the outside faces of the pair to inhibit contamination.

Oil Reservoirs. One method of extending the oil supplied to a bearing is by providing the device that it is in with a reserve supply of oil. Such a source of oil molecules will aid in restricting the loss of oil molecules from the bearing. Sintered nylon plugs or spacers that are vacuum impregnated with the oil are commonly used. There is some question about their effectiveness, but, until that can be determined, they should be continued in use.

Another method of adding oil to the atmosphere surrounding the bearings is to coat the volume surfaces with a film of the oil. Such a film will not only serve to provide an oil atmosphere, thereby reducing the boil off from the bearings, but it will also inhibit the surfaces from becoming a condenser that would rob molecules from the atmosphere.

Labyrinth Seals. Another method of extending the life of the oil supplied to a bearing in non-hermetically sealed systems is by the use of a labyrinth seal between the bearing and the vacuum. In a sense, the shields on the bearing serve in such a capacity, and close-fitting and direction-changing passages outboard of the bearing also serve to decrease the conductance of the oil molecules toward the vacuum. Based on the calculations of many contractors on various systems with different labyrinth designs, the time period required to outgas all of the oil in the bearings and reservoirs of those systems were in the range of many years.

It can be argued that a bearing may fail due to a lack of adequate lubrication, even though the calculations indicate a period of several years are required to outgas all of the oil in the system. This may be true because the bearing is hot or under excessive loads; however, the use of labyrinth seals offers more assurance of success than their nonuse.

Although the incorporation of labyrinth seals is a housing design feature, rather than a bearing feature, it is included in this discussion of desirable bearing conditions because of its importance and close relationship to bearing life, especially when they are lubricated with the more volatile oils.

Tight Packaging. It is highly desirable to know the amount of oil that is within the wear zone of a bearing at the time it is being installed into the intended mechanism. One method of attempting this, that is in common practice, is that of having the bearing manufacturer or vendor make dry and lubricated weight measurements of each bearing during processing and packaging.

A usual packaging method that is used is that of heat sealing the bearing in one or more plastic bags. Invariably, the bags are much larger than the bearing so that, in the subsequent handling, the bearing is relatively free to move about within the inner bag. The sliding motion of the bearing in the bag has resulted in much of the original oil being wicked out of the bearing, as shown in Fig. 9. Accordingly, when the bearing is removed from the package and installed in the mechanism, it may have a lot less oil in it than when initially packaged.

In order to minimize the oil loss to the package, the bearings could be sealed in tight-fitting plastic inner bags, or packaged in vials with spacers to prevent sliding contact with the package. The use of teflon film for the bags, with its lower surface energy and lower wettability, may also aid in avoiding this loss.

UTILIZATION OF INFORMATION

The information presented in this report will have been known in part by some readers, in toto by others, or not at all by still others. The same breakdown may be applied to the responsible personnel of the various bearing manufacturers. However, spacecraft bearing quality problems still exist and are not scarce. This, of course, suggests that the information is not getting to the responsible ones who do not know it in toto, whether they be NASA personnel, contractor personnel, or those of the bearing manufacturer. Or, it may suggest that those responsible for the procurement of the bearing, "left it up to the bearing manufacturer" without any close surveillance of the processing or without adequate inspection of the final product.

In either case, it is hoped that the promulgation of this report will call to the attention of everyone concerned, those areas where more attention should be paid. Such attention should begin with the bearing procurement specification. It should address itself to all of the areas mentioned in this report that are pertinent to the bearings; this attention should include a discussion of the points with the bearing manufacturer to obtain his concurrence.

It should not be necessary to specify government in-plant surveillance at the bearing manufacturer during the bearing processing if he is made aware in the specification that a random sample of the lot will be thoroughly inspected to total disassembly by a knowledgable NASA or non-government facility. Such inspection should include a weight determination, to the nearest 0.0001 gram, of the quantity of oil or grease in the bearing; a chemical analysis of the lubricant to verify its identity and purity; and a thorough visual examination before and after assembly for defects, anomalies, corrosion, contamination, and surface finishes of balls and races and of the condition of the ball cage.

The value of the Mil-Std 206 torque test is questionable for spacecraft bearings for a number of reasons:

1. It is for a small range of small-size bearings.

2. It is conducted with a light-weight oil, which may not be the final lubricant.

3. It is conducted at a very slow speed, e.g., one rpm, where the lubricant shear resistance is low, which usually is not the operating speed in the application.

4. It's results are affected by the bearing's dirt content. Therefore, the test measures cleanliness, perhaps more than bearing quality.

5. The criteria values for acceptance are arbitrary. Therefore, its requirement in the procurement specification would be superfluous.

However, the value of profilometer traces across the ball groove of each inner and outer race, but at high vertical magnification, is more practical. Such traces not only give a general indication of the surface smoothness, but also of its waviness. When made of each race in a procurement lot, the traces can be compared to one another to obtain an idea of the manufacturer's variability, and to permit selection of the best finished bearings. Likewise, circular traces of each race at the ball groove center will give knowledge of the concentricity of the individual races and of the variability of the lot. This is especially helpful in the selection of bearings for applications requiring low jitter. These traces should be specified.

Other requirements that are often omitted from bearing procurement specifications are: hardness measurements on each race, 200x magnification photograph of each inner race ball groove surface, and weight measurements of each bearing before and after lubrication to obtain the final lubrication weight.

CONCLUSION

Until such time that GSFC establishes a stock bearing procurement program, where large quantities of commonly-used bearings would be manufactured and inspected under the same specification and kept in stock for spacecraft applications, bearings will continue to be bought and lubricated on a "few at a time" basis by various contractors. Therefore, the problems of the past may well continue, unless the points presented in this report are incorporated in the procurement.

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8. Fitzsimmons, V. G. and Shafrin, E. G., "The Wettability and Detection of Fluorescent Barrier Films," NRL Report 7391, March 31, 1972.

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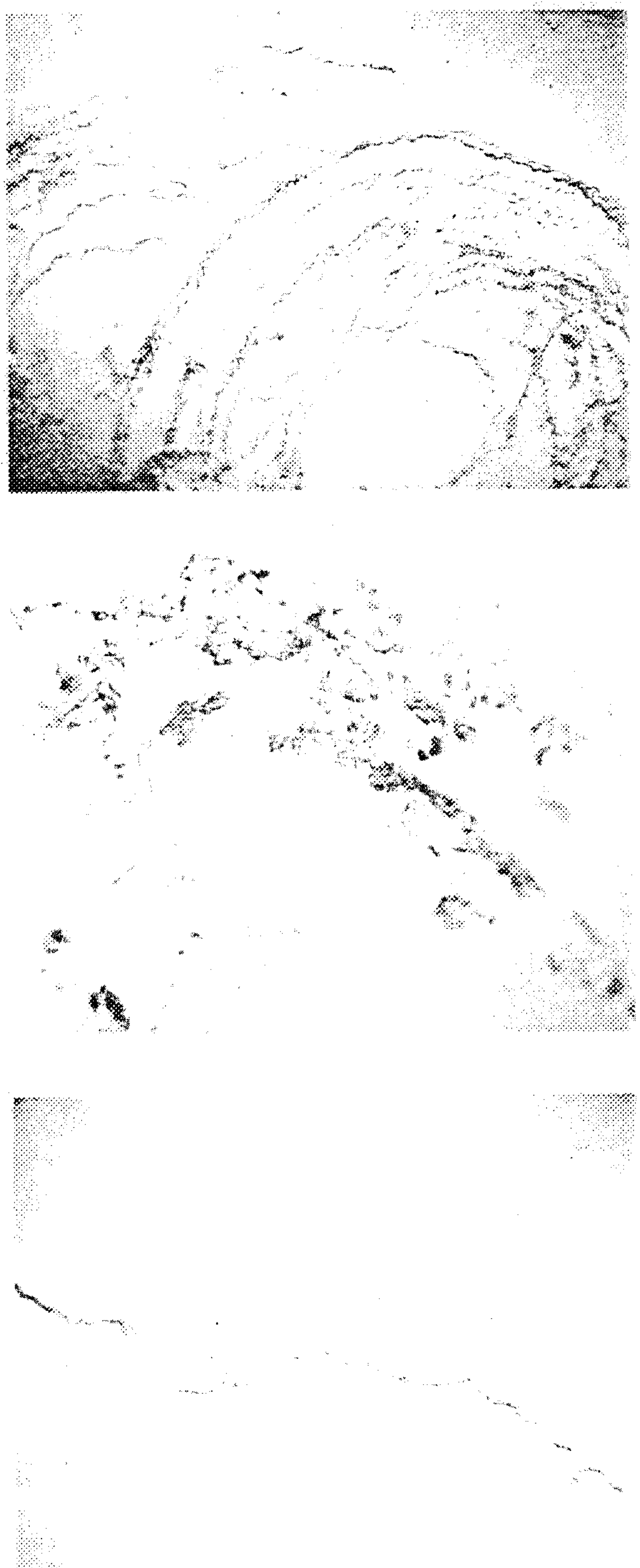


Figure 1

Various Degrees of Surface Damage on Bearing Balls Created During 30 Min. of Ultrasonic Cleaning in Xylene as an Assembled Bearing.

200x

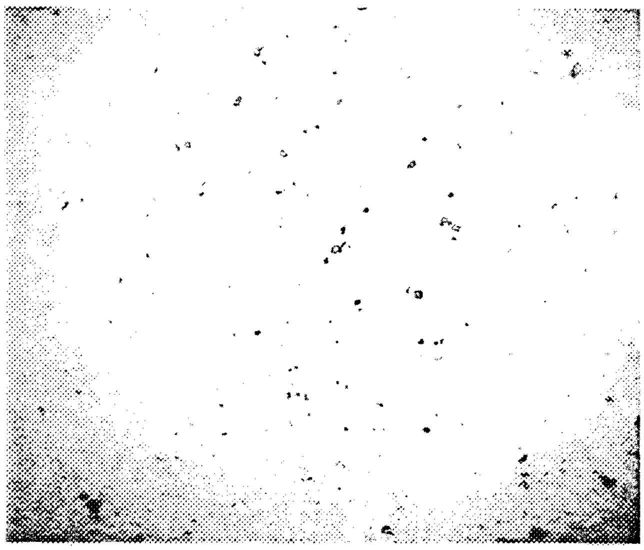


Figure 2

Micropitted Condition on a Bearing Ball Surface Caused by Chemical Passivation.

200x

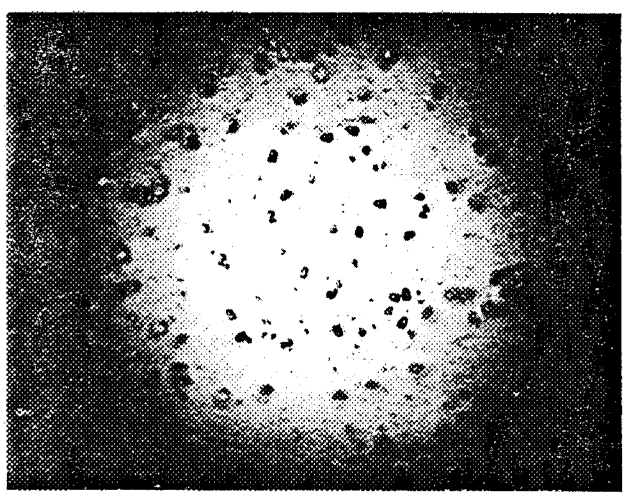
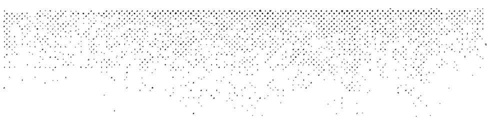


Figure 3

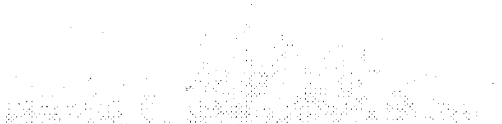
Macropitted Condition on a Bearing Ball Surface Caused by Excessive Chemical Passivation.

200x



Ball Groove Finish on a Ball Bearing Inner Race Before Abrasive-Slurry Tumbling as an Assembled Bearing.

200x



Ball Groove Finish on a Similar Inner Race After the Abrasive-Slurry Tumbling Treatment.

200x

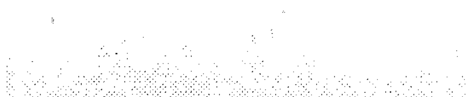


Figure 4

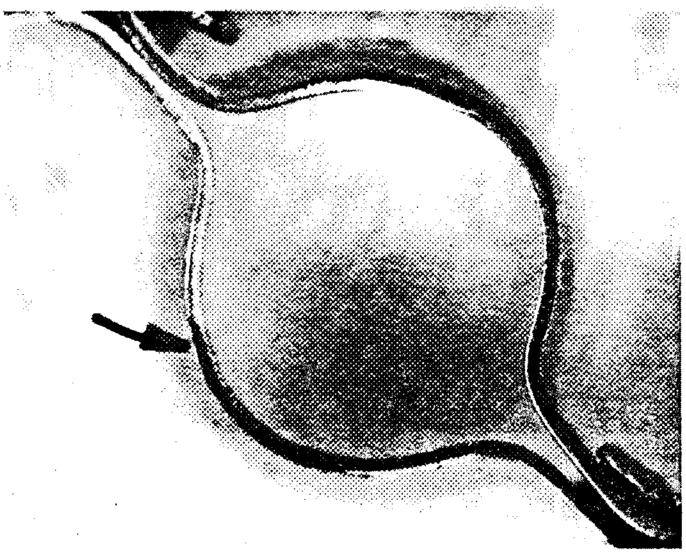


Figure 5

Section of Soft Metal Two-Piece Ribbon Ball Cage Showing Edge (Arrow) Where Cage Rubs Against Race Land.

22x

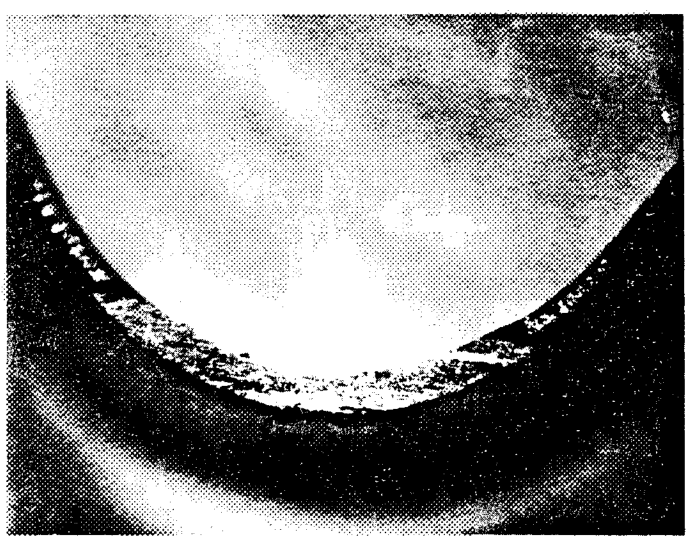
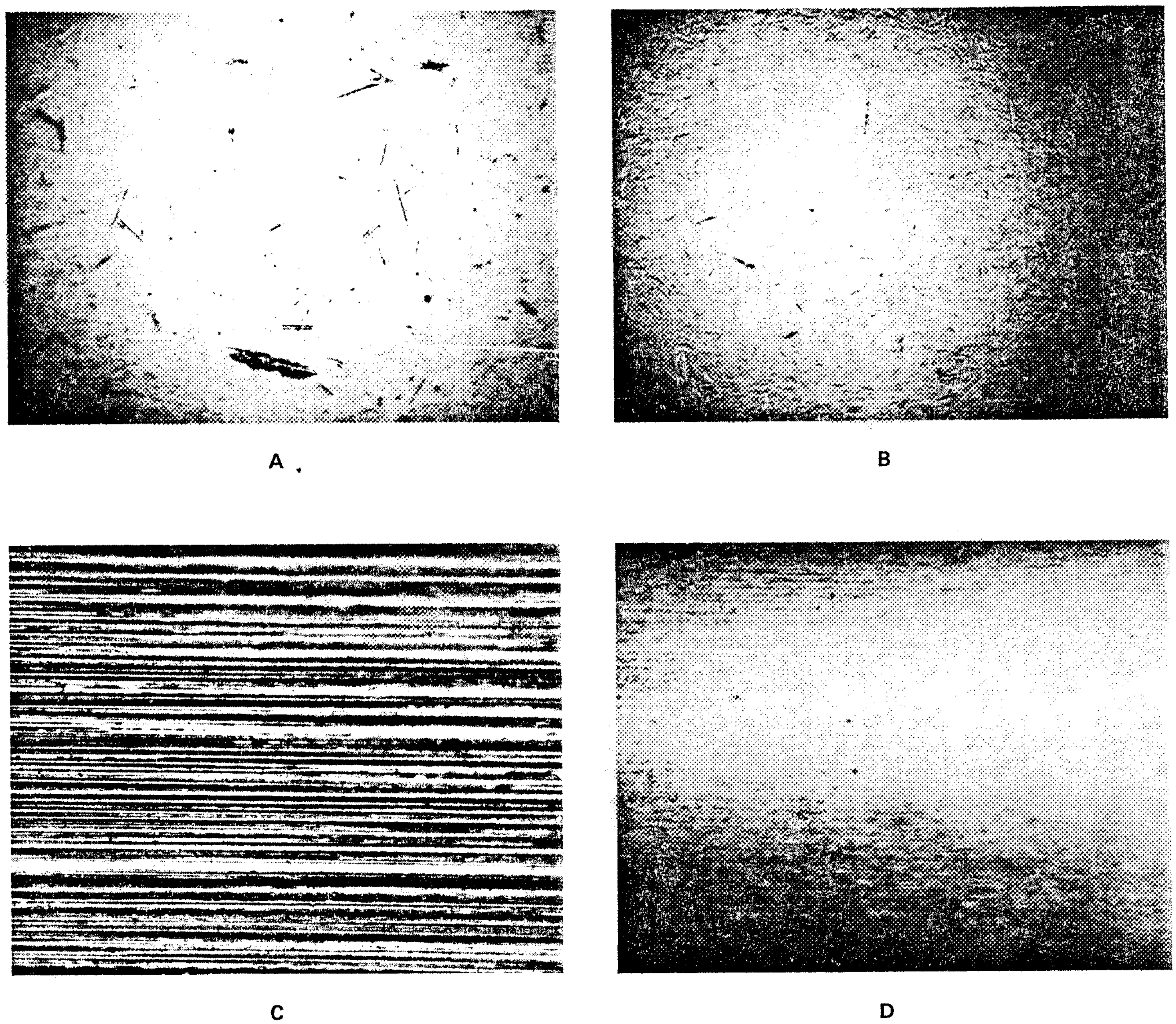


Figure 6

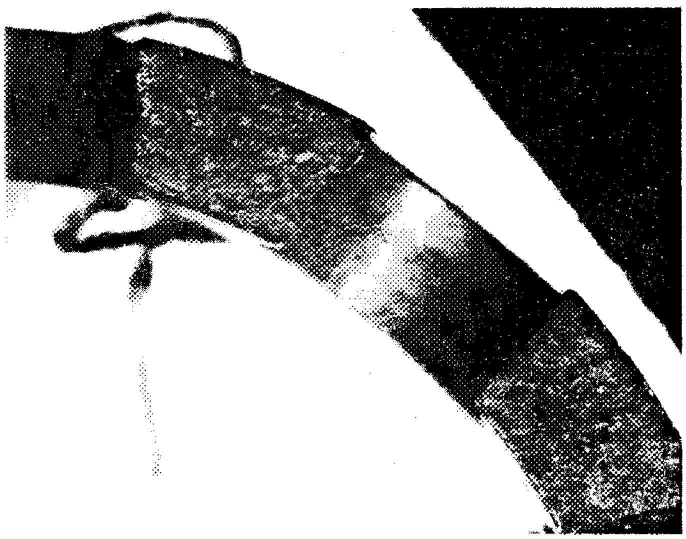
Edge of One Ball Pocket of a Ribbon Cage Showing the Wear That Occurred.

40x



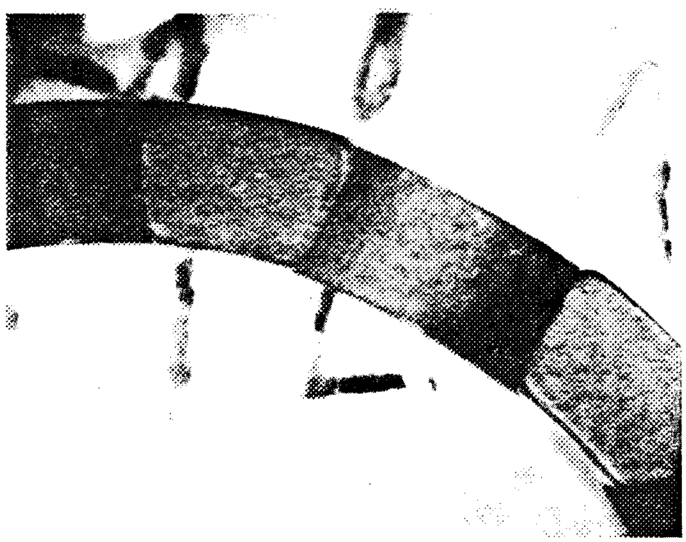
Surfaces of New Bearing Balls (A and B) Showing Poor Surface Finishes. Surfaces of Inner Race Ball Grooves (C and D) Showing a Coarse and a Fine Surface Finish. All Photos at 200x.

Figure 7



Teflon-Base Crown-Type Ball Cage With Sharp Fragile Edges.

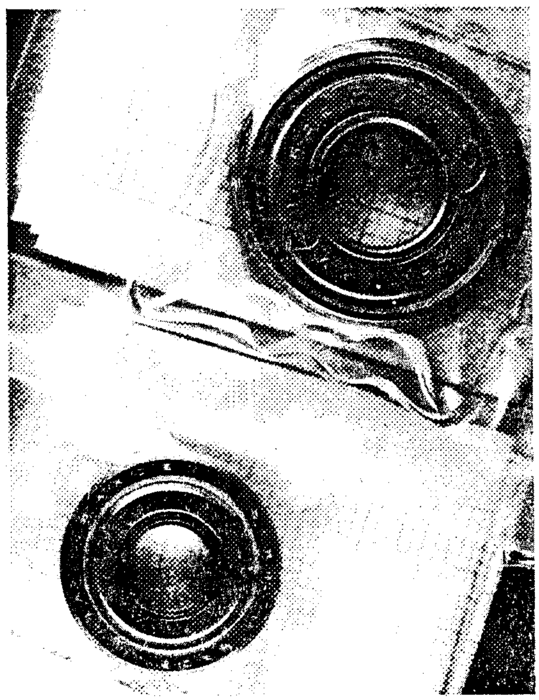
9x



Same Type of Cage From Another Bearing in the Same Lot With Rounded Edges.

9x

Figure 8



Two Bearings as Packaged by the Vendor. Large One Exhibits Oil in the Plastic Bag Which was Wicked Out of the Bearing.

1.7x

Figure 9